

# **UNIFIED MODELS OF TURBULENCE AND NONLINEAR WAVE EVOLUTION IN THE EXTENDED SOLAR CORONA AND SOLAR WIND**

**NASA Grant NAG5-11913**

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## 1. Required Information

Type of report .....	<b>Annual Progress Report</b> (Year 3)
Title of NASA SR&T grant .....	Unified models of turbulence and nonlinear wave evolution in the extended solar corona and solar wind
Name of the principal investigator ..	Dr. Steven R. Cranmer
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Recipient's institution .....	Smithsonian Astrophysical Observatory 60 Garden Street, MS 50, Cambridge, MA 02138 1-617-495-7271 (phone), 1-617-495-7455 (fax)
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## 2. No-cost Extension

The PI (Cranmer) and Co-I (A. van Ballegoijen) would like to initiate our one-time option for a 12-month no-cost extension to this grant. The grant currently expires on 4/30/05 and we request that the performance period be extended 12 months through 4/30/06. The justification is as follows.

The no-cost extension is required to complete the work on the unified model codes (both hydrodynamic and kinetic Monte Carlo) as described in the initial proposal and previous annual reports. Although we are on track to complete the basic/minimal goals of the grant as outlined in the proposal, we have learned so much from the first 2 to 2.5 years of this work that it is now clear that the scope of the unified models should be slightly modified from how they were initially described and planned. Also, the most useful and fruitful aspects of this work only became clear to us in the last year. Additional time to exploit our new understanding of, e.g., the interaction between non-WKB wave reflection and MHD turbulent cascade, would yield a greater fundamental understanding of how the solar wind is accelerated (compared to that obtained if the original plan was followed). Specifically, the extended period of performance will be used to develop new wave source terms for the model codes and run the codes for a wider range of coronal conditions (fast and slow wind) than anticipated initially. We anticipate that the overall impact on solar and space physics coming from this SR&T grant will be greatly increased with the longer period of performance.

## 3. Scientific Accomplishments during the Report Period

The PI and Co-I made substantial progress in Year 3 toward the goal of producing a unified model of the basic physical processes responsible for solar wind acceleration. The approach outlined in the original proposal comprised two complementary pieces: (1) to further investigate individual physical processes under realistic coronal and solar wind conditions, and (2) to extract the dominant physical effects from simulations and apply them to a 1D model of plasma heating and acceleration. The five specific accomplishments listed below are divided into these two main categories:

- 1a. *Focused Study of Non-WKB Alfvén Wave Reflection.* We completed a comprehensive model of Alfvén wave reflection that spans the full distance from the photosphere to the distant heliosphere (Cranmer & van Ballegoijen 2005). As promised in the proposal, the only “free parameter” of this model was the power spectrum of fluctuations *at the photosphere* (as given by, e.g., statistical studies of bright point motions). The energy densities of inward and outward modes were computed self-consistently

at all heights above the photosphere, and a macroscopic MHD prescription for turbulent damping was applied to obtain the plasma heating rate as a function of distance.

- 1b. *Focused Study of Weak-Shock Acoustic Steepening.* Although modeling the solar chromosphere was not included in the initial proposal, we concluded that the most physically realistic way to model the origin of the solar wind is to treat the chromosphere and corona together as a single system. Thus, the hydrodynamic code being developed (see item 2b below) contains a model of chromospheric heating by a spectrum of acoustic waves. All prior time-independent calculations of the acoustic heating, though, used the so-called “weak-shock” theory above the height where shocks are believed to form, with no heating below that height. We developed a new formalism for following the *gradual steepening* of acoustic waves above the photosphere, which naturally produces a smooth (and frequency-dependent) ramp-up of the heating in the low chromosphere as the shock grows in strength. This work was a natural outgrowth of the wave steepening study discussed in § 2.3.2 of our initial proposal.
- 1c. *Focused Study of Collisionless Particle Heating.* In Year 1, our first focused study of kinetic MHD turbulence yielded specific predictions of how the cascaded fluctuation energy should be partitioned into proton, electron, and minor ion heating in the collisionless extended corona. These models, though, were performed at only one height ( $2 R_{\odot}$ ) and only for high-speed solar wind conditions. Since then, other studies (mainly performed by S. P. Gary of Los Alamos) have attempted to extend these results to a wider range of plasma conditions. In the final part of Year 3, we are: (1) folding in the overall results of these studies, as well as (2) performing our own parameterizations of the kinetic partitioning as a function of local plasma conditions *and* the cascade parameters defined by Cranmer & van Ballegoijen (2003, *Ap. J.*, 594, 573).
- 2a. *Unified Model Code: Kinetic Monte Carlo.* We have continued the development and testing of the proton-electron Monte Carlo model code BOREAS. The self-consistent inclusion of ion cyclotron heating (i.e., diffusion in velocity space) has become possible only since the non-WKB reflection model was completed (item 1a above), since the relative amounts of outward and inward wave flux are a key ingredient to how positive ions are heated. This code, though, is no longer the sole thrust of the “unified model” approach of this grant, and it was determined that this code should be completed and run only *after* the macroscopic hydrodynamic code (see item 2b below) is completed.
- 2b. *Unified Model Code: Hydrodynamic Chromosphere/Corona.* The kinetic code described above gives an accurate “microscopic” prediction of particle velocity distribution functions in the accelerating solar wind, but there are three main reasons that a broader “macroscopic” fluid model is needed as well: (1) as described above, we need to treat the chromosphere and corona as a unified system if realistic mass loss rates are to be predicted, (2) it is helpful to have the ability to rapidly evaluate the self-consistent coronal plasma conditions from various models of the bulk plasma heating rate as a function of height (from the chromosphere to the outer solar wind), and (3) the best way to model the *ab initio* causes for the existence of fast vs. slow solar wind is to use models that extend down to low atmospheric heights where the boundary conditions are the *same* for, e.g., coronal holes vs. streamers. Because a single Monte Carlo particle code (like BOREAS) cannot extend over so many orders of magnitude in density as we require, I have written the ZEPHYR code as a hydrodynamic complement to the above kinetic code. The ultimate result of this SR&T program should involve coupled runs of these two codes. ZEPHYR uses a newly developed relaxation technique to solve for the steady-state one-fluid 1D photosphere, chromosphere, corona, and wind conditions for a general late-type star.

Currently in final beta-testing mode, the code includes chromospheric shock heating, Alfvén wave pressure and turbulent heating terms, an up-to-date description of radiative heating and cooling, and a realistic transition from classical (Spitzer-Härm) to non-classical (saturated) heat conduction.

#### **4. Comparison of Accomplishments with Proposed Goals**

The proposal contained two specific objectives for Year 3: (1) to complete the unified model code, and (2) to apply it to various kinds of coronal holes (and polar plumes within coronal holes). Although the anticipated route toward these two final goals has changed (see accomplishments 2a and 2b above), they remain the major milestones for the extended period of performance. Accomplishments 1a and 1c were necessary prerequisites for the derivation of “physically relevant transport and mode-coupling terms” for the unified model codes (as stated in the proposal Year 3 goals). We have fulfilled the proposed “core work” to study 4 general types of physical processes; in previous years we studied turbulence, mode coupling (i.e., non-WKB reflection), and kinetic wave damping, and accomplishment 1b provides the fourth topic: nonlinear steepening.

#### **5. Publications and Conference Presentations**

The non-WKB Alfvén model was published by Cranmer & van Ballegoijen (2005), *Ap. J. Supp.*, 156, 265. The model results from this paper were presented at the May 2004 SPD/AAS meeting in Denver. I was invited to give a 30-minute review talk on “New Insights into Solar Wind Physics from *SOHO*” at the 13th Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun, in Hamburg, Germany, July 2004 (see proceedings paper at astro-ph/0409260). I also gave an invited talk at the *SOHO*-15 Workshop in St. Andrews, Scotland in September 2004 (see astro-ph/0409724). Both of the above invited talks contained summaries of the overall research done under this SR&T grant. Further progress reports on the unified models will be presented at the May 2005 SPD/AGU Meeting in New Orleans and the June 2005 Solar Wind 11 (*SOHO*-16) Workshop in Whistler, Canada.

As a semi-related activity (not specifically covered by this grant), the PI also published a paper presenting a closed-form explicit solution to the isothermal Parker solar wind equation, which was not possible prior to the introduction of the so-called “Lambert W function” in the 1990s (see Cranmer 2004, *Am. J. Phys.*, 72, 1397).

#### **6. Statement of Work for the Next Report Period**

The Work Plan for the following year (May 1, 2005 to April 30, 2006) is as follows. The PI will finish coding and testing the unified model codes BOREAS and ZEPHYR. The PI and Co-I will finish the derivation of useful parameterizations of the kinetic partitioning results from Year 1 (see item 1c above) and the non-WKB wave reflection results from Years 2–3 (see item 1a above). The model codes will be applied not only to coronal holes (as proposed) but also to streamers and other potential source regions of the slow solar wind, since *all* coronal regions seem to share roughly similar photospheric and chromospheric lower boundary conditions.

No additional funds are requested.